ENHANCED TECHNIQUE FOR 3D NONLINEAR FEM ANALYSIS OF PILE FOUNDATION

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ABSTRACT: This study aims to resolve the computational difficulties in finite element analysis of pile foundations. Finite element mesh for the analysis of pile foundation includes nonlinear frame elements and three-dimensional soil elements apart from interface elements to represent the soil-pile interaction. Nonlinear FEM analyses with such 3D elements demand more powerful computation environment and takes longer time than linear and two-dimensional analyses. This study explores the possibility of relaxing these computational requirements without compromising the accuracy of the analytical results. First, it is analytically proved that when a nonlinear pile is subjected to lateral displacement, only a portion of pile length closer to the surface is activated. Hence, the total number of elements and the computation time can be substantially reduced if the analysis domain is restricted within the activated length. Next, a mesh condensation scheme is proposed for foundation consisting of large number of piles, and its performance and accuracy is analytically verified. The results showed that the proposed mesh condensation technique significantly enhances the computational efficiency without influencing the results.

KEYWORDS: FEM analysis, computation time, 3D soil elements, nonlinear pile, activated length, pile-group, mesh condensation.

1. INTRODUCTION

Recently, construction of foundation consisting of hundreds of piles is becoming more common. As the experimental study of such large-scale soil-pile structures is costly, hectic and time consuming, computation using finite element analysis serves as a more convenient alternative for the performance evaluation of such structures. In the FEM analysis of underground structures, three-dimensional elements with many nodes are needed to represent the surrounding soil. In order to negotiate with the far field effect and mesh sensitivity, sufficiently large cross-sectional domain and reasonable element size should be considered during the mesh discretization. Consequently, total number of nodes, elements and the degrees of freedom become large, which is further increased due to finer vertical discretization throughout the foundation depth. Hence, the performance evaluation of such large-scale foundations through 3D FEM analysis takes longer, a situation most designers would like to avoid.

In this study, conceptual guidelines to reduce the depth of analysis domain and to condense the mesh in horizontal plane are proposed. The bearing-capacity based design criteria of a pile might lead to considerably longer pile if the soil is cohesive and a stiff stratum is located very deep. However, the lower part of a pile foundation remains passive during lateral loading, and can be omitted from the FEM mesh without affecting the result. Similarly, the authors feel that replacing a few piles in a pile-group with a single pile at the centroid and multiplying its response with a group factor equal to the number of replaced piles will not influence the result, but will certainly reduce the number of elements and, hence, the required computation time.

2. ANALYTICAL TOOL AND SIMULATION

A three-dimensional nonlinear finite element analysis program called COM3 (*Co*ncrete *M*odel in *3*D) [1] is used in this study. As illustrated in Figure 1, basic components of a reinforced concrete pile foundation consist of a pile, surrounding soil and soil-pile interface. In COM3, RC piles are

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represented by frame elements that are further divided into concrete and reinforcement fibers. Concrete fiber response in compression is computed by the *elasto-plastic and fracture model* [2] supplemented by the *spalling model* [3] for cover concrete fibers. *Tension softening/stiffening model* [2] is used to compute the tensile response of concrete. Similarly, average stress-strain relationship used for reinforcement takes into account the bond effect in tension and buckling in compression [3].

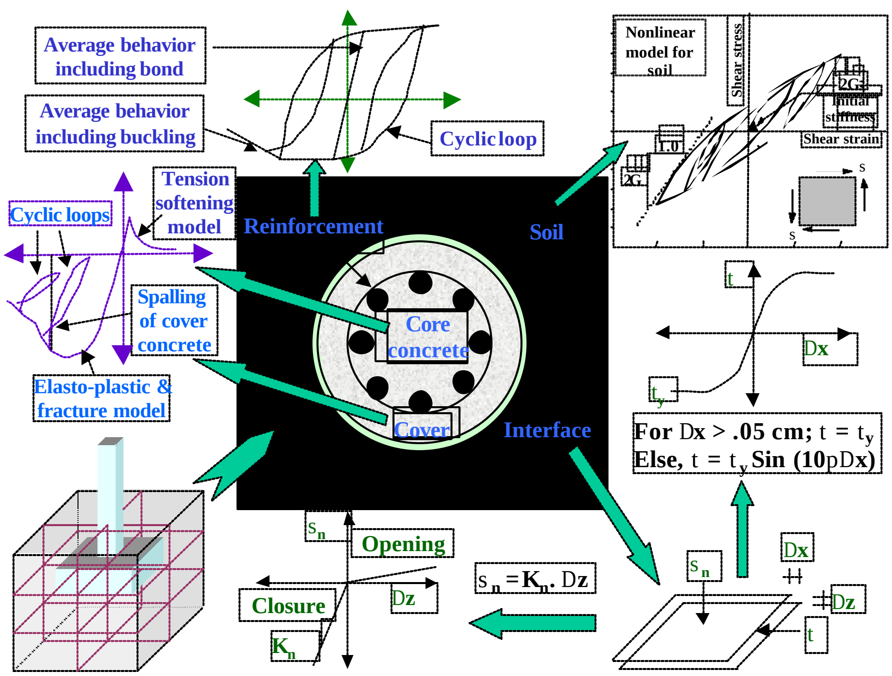

Figure 1. Basic components of soil-pile analysis

In COM3, three-dimensional elements with 20 nodes are used to represent soil, and dimensionless interface elements are used to incorporate soil-pile interactions. The nonlinear skeleton curve of the shear stress-strain relationship of soil is derived from *Ohsaki's model* [4]. Similarly, the interface elements are analyzed with *nonlinear interface model* [3] that takes into account the two-way interaction between the normal and transverse directions. Note that the nonlinear material models used in COM3 are fully path-dependent, and have been experimentally verified for cyclic as well as dynamic loading of reinforced concrete and soil [2, 5].

3. GENERAL BEHAVIOR OF NONLINEAR RC PILE

For qualitative verification of the aforementioned analytical models, lateral loading test of a reinforced mortar pile confined in sandy soil is considered here [6]. As shown in Figure 2, the height of the soil specimen is 800 cm and the cross section is 250×250 cm square. The pile is located at the center of the soil and it extends from the top to the mid-depth of the soil. The compressive strength of mortar is 22.4 Mpa, and a compressive stress of 2 MPa is applied at the top of the pile. The pile is circular with 15 cm diameter and is reinforced with six numbers of 6 mm diameters deformed bars, the reinforcement ratio being 0.96%. The soil layers in the upper half have the density of 0.0014 kg/cm^3, and the SPT value ranges from 0 to 10. Whereas, for the lower half, the soil density is 0.0017 kg/cm^3, and the corresponding SPT value is around 40. The soil boundary is fixed throughout the depth, and cyclic lateral displacements are applied to the pile cap, which is restrained against rotation. The test setup and the comparison of analytical and experimental results are illustrated in Figure 2.

Although the pile used in the experiment was made of mortar, concrete constitutive models are used in the analysis. Moreover, the rotation at the pile top is completely prevented by fixing the topmost node although small rotation may have occurred in the test. Consequently, slightly higher stiffness can be observed in the analytical load-displacement relationship. Otherwise, the analytical and experimental results are satisfactorily closer to each other.

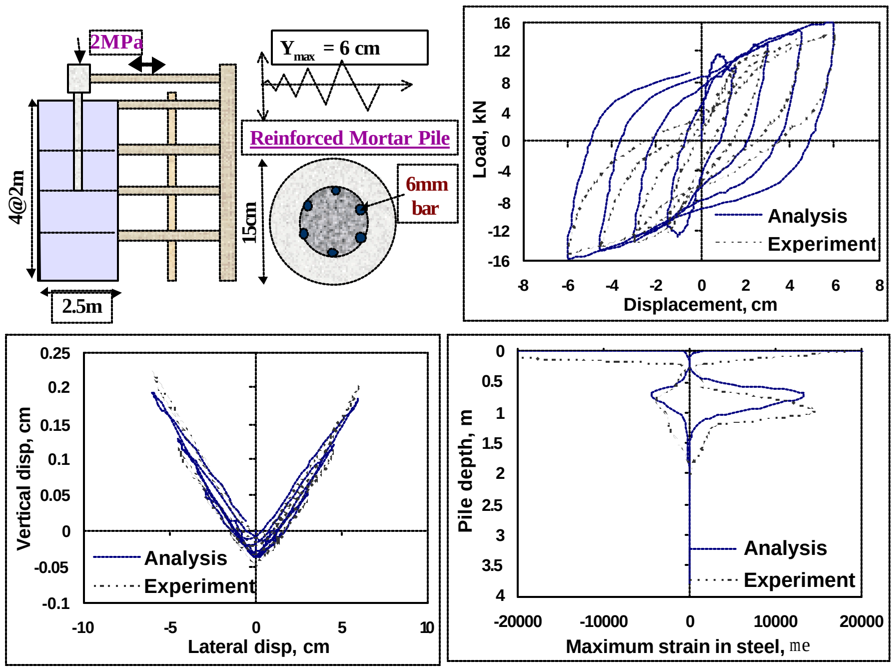

Figure 2. General behavior of nonlinear reinforced concrete pile subjected to lateral loading

It can be noticed in the maximum strain profile of reinforcing bars that a plastic hinge forms at around 1 m depth, and virtually no strain is induced in the lower half of the pile length. It indicates that only the upper half of the pile length was activated. A similar analysis was conducted considering only the upper 3 m (i.e. omitting the lower 5 m from the earlier analysis domain). The analysis took around one-third of the original computation time but the result was similar to that in Figure 2. It proves that the lower inert part of the underground piles can be disregarded in the analysis to relax the computational requirement. More detailed analytical parametric study is carried out by the authors [3], which concluded that the activated length increases with increase in the ratio of pile diameter to soil stiffness. However, the explicit way to compute the activated length is not yet formulated and should be addressed in the near future.

4. MESH CONDENSATION TECHNIQUE FOR PILE GROUP ANALYSIS

In 3D finite element analysis of pile foundation, each one-dimensional element representing the interface and the pile should coincide with one of the boundaries of 3D soil elements to enforce the compatibility condition. Hence, number of 3D soil elements must increase with the number of piles in a pile-group analysis, rendering the computation slower. Sometimes, the capacity of computational facility may not be sufficient for analyses of foundation with very large number of piles. Using the conventional mesh discretization method, such situations are indispensable and the extensive analytical study of such structures seems unfeasible.

Here, a mesh condensation technique is introduced to reduce the total number of 3D soil elements. In this technique, a few piles within a large group are replaced with a single pile at the center of the piles replaced. This representative pile has similar dimension as individual piles in the group, but the response of this pile is multiplied by a *group factor* equal to the number of piles replaced. It is to be noted that this technique cannot replace all piles in a group with a single pile, as the response might be influenced by group effect [7]. However, in a soil-pile domain containing large number of piles, the replacement of a few piles with a single pile is not expected to influence the result significantly.

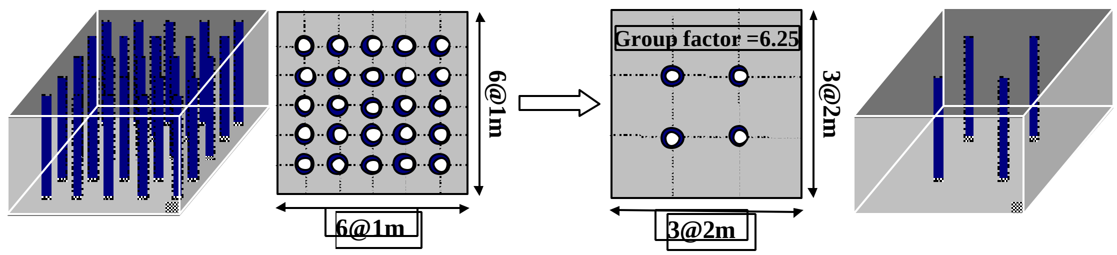

Figure 3. Mesh condensation scheme for pile group analysis

Hereafter, a group of 25 piles subjected to monotonic lateral displacement is considered for the verification of the aforementioned technique. The conventional and condensed meshes are shown in Figure 3. The soil domain considered in the analysis is 6×6 m and the depth is considered to be 1 m. The surrounding soil is assumed to be sandy with initial shear modulus of 80 MPa and shear strength of 0.1 MPa. The circular steel piles are hollow with 80 cm external diameter, 5 cm thickness, and are spaced 1 m apart. The steel pile is assumed to have the following mechanical properties: yield strength f_y = 350 MPa, and Young's modulus E_s = 200 GPa. Next, these 25 piles are replaced with four piles spaced at 2 m apart, each of them having a *group factor* equal to 6.25.

5. RESULTS AND DISCUSSIONS

First, the pile group is subjected to lateral load at the pile top without any axial load and bending moment. Four different conditions are considered as follows: (i) free soil boundary and free pile top, (ii) free soil boundary and fixed pile top, (iii) fixed soil boundary and free pile top, and (iv) fixed soil boundary and fixed pile top. The load-displacement curves obtained from the analyses with the conventional mesh (25 piles) and the analysis using the condensed mesh (4 piles with group factor 6.25) are shown in Figure 4. As expected, the analyses using the condensed mesh were significantly faster (about 5 times) than the detail analyses. Nevertheless, the results from both analyses are close to each other for all four cases, justifying the reliability of the proposed mesh condensation technique.

For more practical verification, pile groups are analysed with axial load and bending moment applied at the pile cap to include the effect of superstructure. The combination of axial load and moment in the pile cap is represented by linearly varying axial load across the pile cap. In these analyses, pile top is simulated as a fixed node to represent the restraining action of pile cap, and free and fixed soil boundary conditions are considered. Two different combinations of axial load and moment are adopted for each boundary condition. The first combination considers axial tension at one end and equal axial compression at the other end of the pile cap with a linear variation in between to represent pure bending. In contrast, the second combination considers all piles in axial compression, linearly increasing from one end to the other, to represent a combination of axial load and bending moment. The analytical load-displacement curves for all four cases are shown in Figure 5. The results from analyses considering the conventional mesh and the condensed mesh are close to each other except around the transition from elastic to plastic phase, where the condensed mesh slightly overestimates

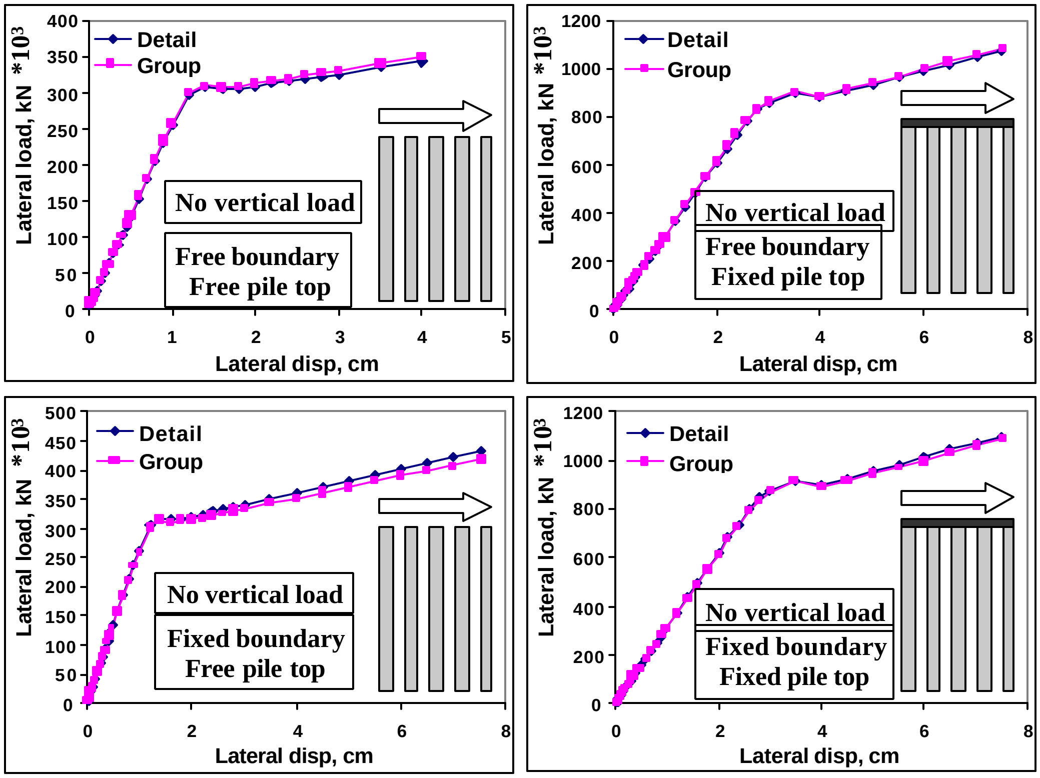

Figure 4. Analysis of pile group subjected to lateral load

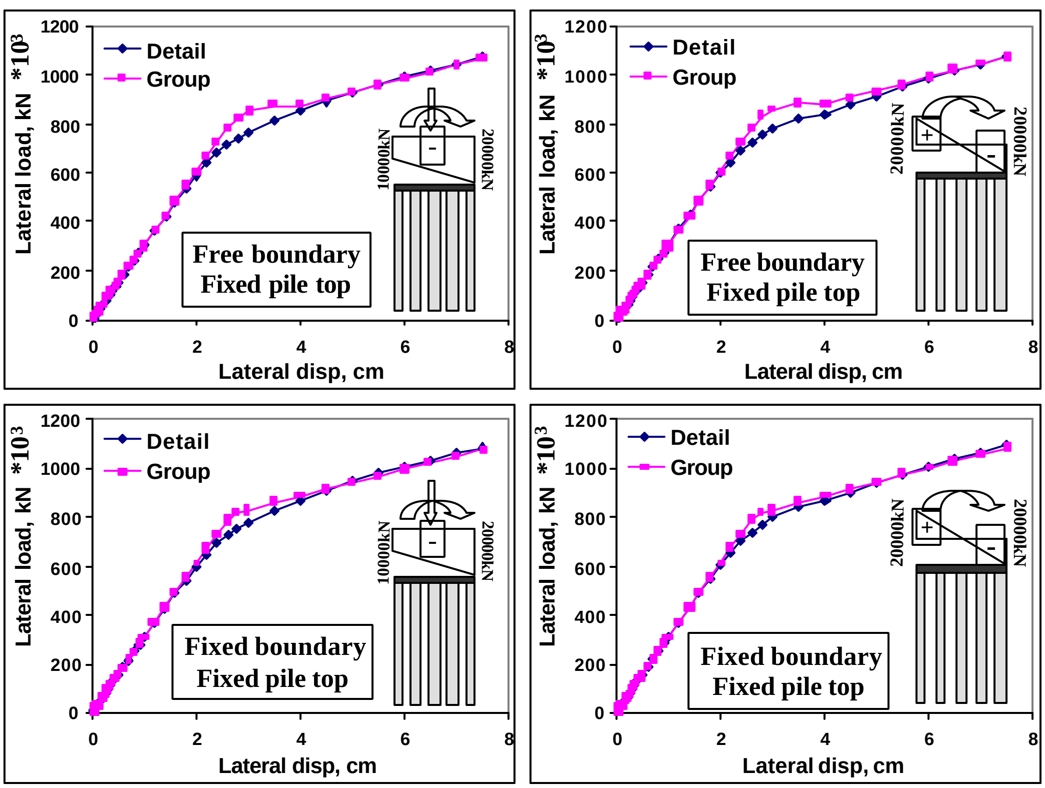

Figure 5. Analysis of pile group subjected to lateral load, axial load and moment

the load. This is because of the gradual yielding of few piles in detail mesh is represented by the abrupt yielding of the representative pile in the condensed mesh.

The accuracy of the condensed mesh analyses for all load combinations and boundary conditions is sufficient for engineering purpose. These verifications give ample evidence that the proposed mesh condensation technique can be reliably used in 3D FEM analysis of pile group embedded in soil. Piles in a large group should be divided into smaller groups, and each small group should be replaced with one pile at the centre of the replaced pile group. The dimension of the representative pile is same as the individual pile and its response should be multiplied by a group factor equal to the number of piles in the replaced pile group to get the overall response. This method significantly reduces the required computer capacity as well as the computation time, and makes it possible to check the performance of huge foundations having too many piles using 3D nonlinear FEM analysis.

6. CONCLUSIONS

Three-dimensional and nonlinear finite element analysis of soil-pile system was performed. The analytical results showed that only the upper part of reinforced concrete pile is activated during lateral loading because of the formation of plastic hinge, and the pile length does not have any effect on the lateral response provided that the pile is longer than the activated length. This information permits us to neglect the lower part of soil-pile domain in FEM analysis so that the number of 3D soil elements is significantly reduced and the computation speed is greatly enhanced. Similarly, a method to efficiently analyze a massive soil-pile structure with a large number of piles was also proposed and verified. By replacing a few piles in a pile-group with a single pile, the number of three-dimensional soil elements can be significantly reduced, and the computation time as well as required computer capacity can be greatly reduced. The results using the proposed mesh condensation technique were found to be sufficiently close to the results obtained from detail analysis of pile groups subjected to the combination of axial load, bending moment and lateral displacement.

7. REFERENCES

[1] Maekawa, K., *General Information for COM3 Version 9.5*, Dept. of Civil Engineering, The University of Tokyo, March 2000.

[2] Okamura, H. and Maekawa, K., *Nonlinear Analysis and Constitutive Models of Reinforced Concrete*, Gihodo Publication, Tokyo, 1991.

[3] Dhakal, R.P., *Enhanced Fiber Model in Highly Inelastic Range and Seismic Performance Assessment of Reinforced Concrete*, Doctoral Dissertation, Dept. of Civil Engineering, The University of Tokyo, 2000.

[4] Ohsaki, Y., *Dynamic Characteristics and One-Dimensional Linear Amplification Theories of Soil Deposits*, Research Report 82-01, Dept. of Architecture, The University of Tokyo, 1982.

[5] Dhakal, R.P., Salem, H. and Maekawa, K., "Nonlinear Analysis of Laterally Loaded Reinforced Concrete Piles," *Proceedings of the Seventh East Asia-Pacific Conference on Structural Engineering and Construction (EASEC7)*, Kochi, Vol. 1, 1999, pp. 740-745.

[6] Tsuchiya, T., Nakajima, M., Kakurai, M. and Yamashita, K., "Lateral Failure Loading Test of RC Pile with Fixed Pile-Head Against Rotation", *Proceeding of the Annual Conference of Japan Architecture Society*, 1996 (*In Japanese*).

[7] Brown, D.A. and Morrison, C., "Lateral Load Behavior of Pile Group in Sand", *Journal of Geotechnical Engineering, ASCE*, Vol. 114, No. 11, 1988, pp. 1261-1276.